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RHIC Performance*

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The Brookhaven Relativistic Heavy Ion Collider (RHIC) is the first hadron accelerator and collider consisting of two independent rings. It is designed to operate at high collision luminosity over a wide range of beam energies and with particle species ranging from polarized protons to heavy ions. Construction of RHIC was officially completed in 1999. An overview of the status of commissioning and machine performance for the first operation period with gold beams is given.

1. RHIC HEAVY ION COMMISSIONING AND OPERATION

After an initial engineering run during 1999 cool-down of the two 3.8 km long cryostats containing about 1000 super-conducting magnets started in February 2000 and operation with gold beam, delivered by the injector chain consisting of the Tandem, Booster, and AGS, started in April. First collisions in all four collider experiments were observed during June 2000 at an initial beam energy of about 28 GeV/nucleon. Collisions at this years target energy of about 65 GeV/nucleon and operation at a luminosity of up to $2 \times 10^{25}\ cm^{-2}\ s^{-1}$ was established during July and August.

Fig. 1 shows the layout of RHIC and the three injector accelerators Tandem, Booster and AGS. The gold ions are stepwise ionized as they are accelerated to RHIC injection energy, at which point they are fully ionized. The performance of the injector is summarized in Table 1. The Tandem Van de Graaff accelerates Au^{-1} from a sputter source to about 1 MeV/nucleon. The 530 ms long beam pulse is stripped to Au^{+32} and injected into the Booster using horizontal and vertical phase space painting. After acceleration to about 100 MeV/nucleon the beam is stripped to Au^{+77} and transferred to the AGS where it is accelerated to the RHIC injection kinetic energy of 8.6 GeV/nucleon. During acceleration in the AGS the beam bunches from the Booster are merged to reach the required intensity of about 1×10^9 Au ion per bunch at a longitudinal emittance of 0.3eVs/nucleon. The final stripping to bare Au^{+79} occurs on the way to RHIC.

Initial commissioning of RHIC focussed on the magnet power supply control during injection and acceleration. The two RHIC rings, labeled blue and yellow, are intersecting at six interaction regions (IR), four of which are occupied by the collider experiments BRAHMS, STAR, PHENIX and PHOBOS, respectively. To achieve the necessary flexibility to adjust and optimize the collision rate at each interaction region of the two RHIC rings a very large number of independently controllable power supplies were installed and

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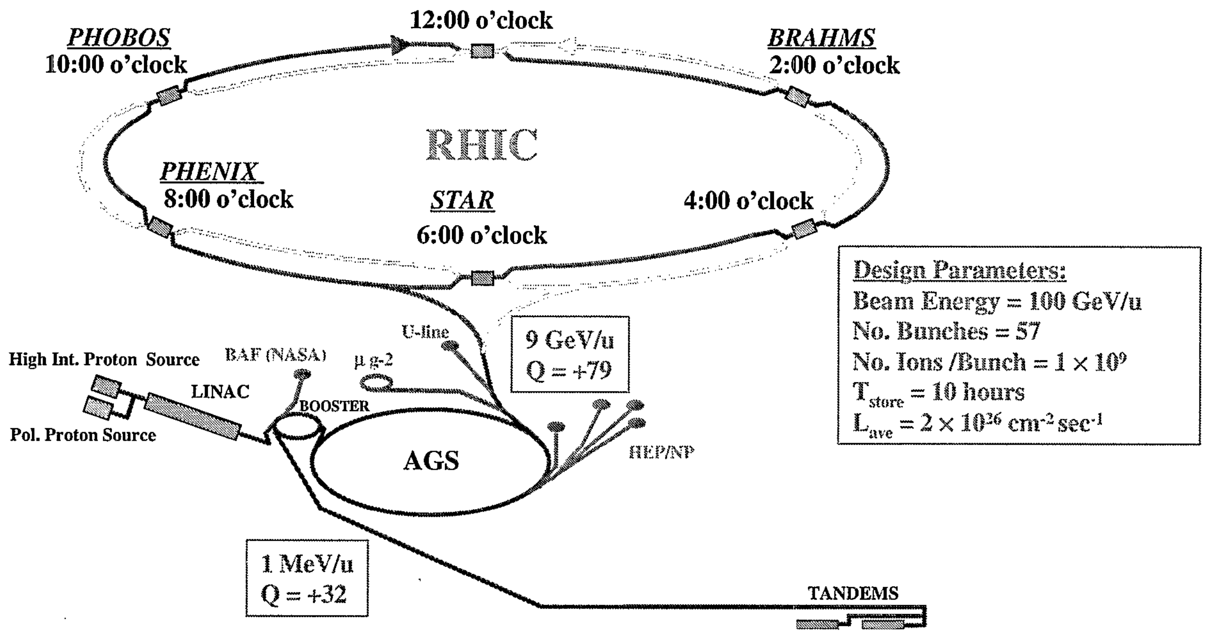

Figure 1. Layout of RHIC and the injector accelerators. The gold ions are stepwise ionized as they are accelerated to RHIC injection energy.

needed to be commissioned. Very precise and reliable beam position monitors were available early on in the commissioning effort and allowed beam-based diagnostics to detect hardware problems. They also allowed the demonstration of the excellent agreement of the RHIC machine lattice functions with the design.

Table 2 gives the goals for the main machine parameters for the commissioning and first operations period, all of which were either reached or exceeded during the run. The energy at storage of 66 GeV/nucleon is less than the design energy of 100 GeV/nucleon because the large-bore superconducting dipole magnets used to merge and separate the two beams on either side of the interaction regions require in-situ training to reach their design strength. For this first run this was postponed until the end of the run at which time design performance for these magnets was achieved successfully.

RHIC is also the first superconducting, slow ramping accelerator that crosses transition

Table 1
RHIC injector performance

Location	Intensity normalized to a single RHIC bunch	Efficiency
Tandem	3.8×10^9	
Booster Injection	2.2×10^9	58%
Booster Extraction	1.8×10^9	81%
AGS Injection	0.9×10^9	50%
AGS Extraction	0.9×10^9	95%
Total		23%

Table 2
Parameters and performance goals for RHIC RUN2000

Injection energy	$\gamma = 10.25$ ($P = 9.5$ GeV/c/nucleon)
Storage energy	$\gamma = 70$ ($P = 65.1$ GeV/c/nucleon)
Bunch intensity	0.5×10^9 Au ions/bunch
Number of bunches	56 filled bunches (4 empty bunches for abort gap)
Transverse emittance	$15\pi\ \mu m$ (normalized, 95%)
Longitudinal emittance	0.3 eVs / nucleon / bunch
Beta-functions @ IRs	$\beta^* = 3\ m$ @ 2,4, 8,and 12 o'clock
	$\beta^* = 8\ m$ @ 6, and 10 o'clock
Luminosity	$2 \times 10^{25}\ cm^{-2}\ s^{-1}$ (10 % of design luminosity)
Integrated luminosity	a few inverse micro-barns

energy during acceleration. At transition energy the spreads of the particle revolution frequency stemming from the spread in velocity and spread in path length cancel exactly and all particles maintain their relative position for a long time. Interaction between particles can then cause instabilities. Although some beam loss and longitudinal emittance growth was observed in RHIC from crossing transition energy the effect was not excessive due to the still lower beam intensity and the special machine lattice used during this first run that minimized momentum dependent (chromatic) effects at transition. To reach full design intensity of 1×10^9 Au ions/bunch pulsed quadrupole power supplies will be

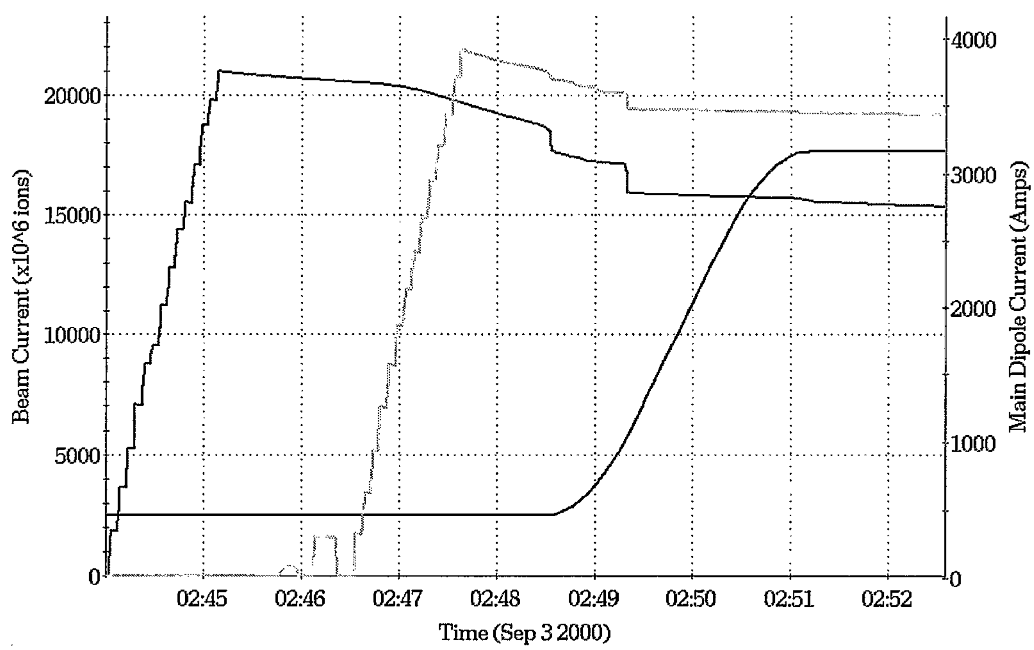

Figure 2. Beam intensity evolution during filling and acceleration in RHIC. The dark and light 'staircase' lines are the beam intensity in the blue and yellow ring, respectively. The third line shows the main dipole current and is proportional to the beam momentum.

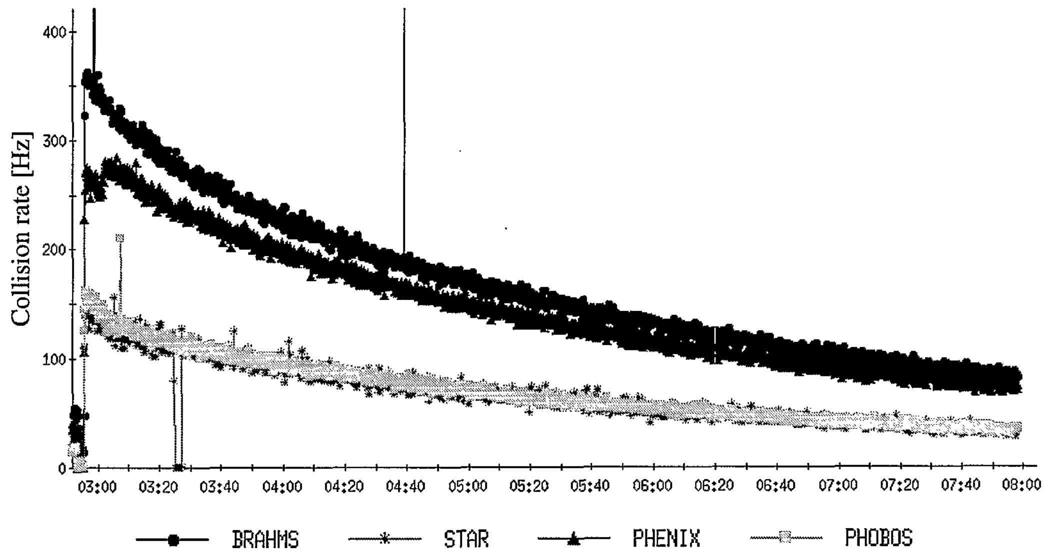

Figure 3. Evolution of the collision rate at the four RHIC detectors during a typical store.

installed to change transition energy quickly during acceleration to effectively jump across it.

Fig. 2 shows a typical acceleration cycle which includes filling the blue ring with 56 bunches in groups of 4 bunches, filling the yellow ring in the same way and then simultaneous acceleration of both beams to storage energy. Residual loss of beam that was not captured by the rf system occurs at the beginning of acceleration and from transition crossing about one minute later. Beam losses due to the two beams interacting is also noticeable at injection energy.

During the last month all four experiments were in data taking mode. Typical stores lasted about 5 hours. Fig. 3 shows the evolution of the collision rate in the four experiments during a typical store. After optimizing longitudinal and transverse steering the initial observed collision rate agreed well with the expected rate as calculated from the beam parameters listed in Table 2 which is 314 Hz for BRAHMS and PHENIX. Note that since STAR and PHOBOS are located at the interaction regions with $\beta^* = 8\ m$ their collision rates are reduced by a factor of 8/3 from the rates of the other two detectors. The drop of luminosity during the store is due to both beam loss and transverse emittance growth most likely caused by the non-linearities of the beam-beam interaction and Coulomb (intra-beam) scattering within a bunch. The latter is particularly important for these fully stripped, highly charged gold beams.

The collision rate was measured using identical Zero Degree Calorimeters (ZDC) at all four interaction regions. The ZDC counters detect at least one neutron on each side from mutual Coulomb and nuclear dissociation with a total cross section of 10.7 barns at 65 GeV beam energy[1]. The peak luminosity for the initial rate shown in Fig. 3 is then $3.3 \times 10^{25}\ cm^{-2}\ s^{-1}$ for BRAHMS and the average luminosity for the store is $1.7 \times 10^{25}\ cm^{-2}\ s^{-1}$. Independent determination of the luminosity using Vernier scans gives a cross section for the ZDC counts of 9.1 ± 1.8 barns[2] which is consistent with the

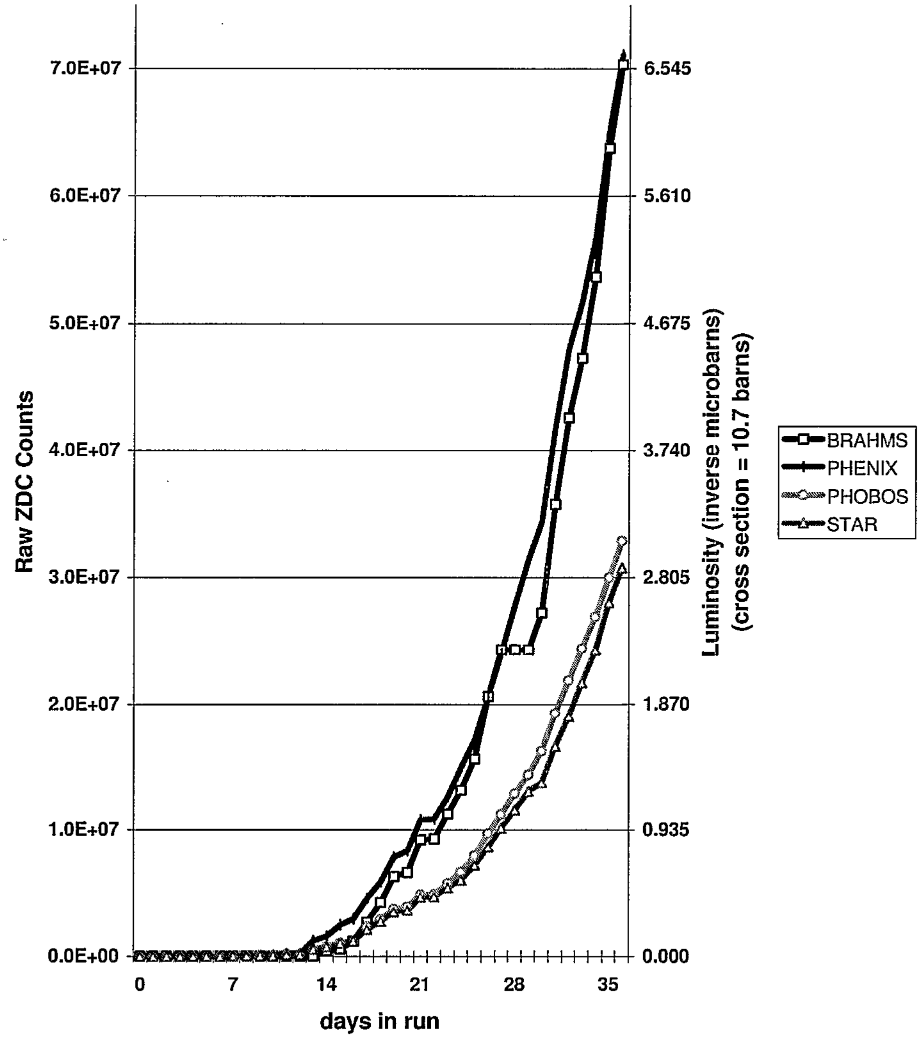

Figure 4. Integrated luminosity of the four RHIC experiments.

results given above. The overall average luminosity for BRAHMS during the last 6 days of the run was 0.8×10^{25} cm^{-2} s^{-1} which gives an availability of 47%. The integrated luminosity over the run is shown in Fig. 4 and exceeded 6 $(\mu b)^{-1}$ for BRAHMS and PHENIX.

2. PLANS FOR RUN2001

The performance goal for the upcoming run in 2001 is to reach design parameters as summarized in Table 3. The main new hardware systems consist of power supplies for the transition energy jump, as mentioned above, and a high gradient, high frequency rf system to avoid emittance growth and beam loss from intra-beam scattering during store. With the new, high frequency rf system significantly shorter Au bunches can be produced and maintained resulting in a collision diamond length of about 20 cm rms.

Table 3
Parameters and performance goals for RHIC RUN2001

Injection energy	$\gamma = 10.25$ ($P = 9.5$ GeV/c/nucleon)
Storage energy	$\gamma = 107.4$ ($P = 100.0$ GeV/c/nucleon)
Bunch intensity(N_b)	1.0×10^9 Au ions/bunch
Number of bunches(N)	56 filled bunches (4 empty bunches for abort gap)
Transverse emittance(ϵ)	15π μm (normalized, 95%)
Longitudinal emittance	0.3 eVs / nucleon / bunch
IR beta-functions at injection	$\beta^* = 10$ m @ all interaction regions
IR beta-functions at store	$\beta^* = 2 - 10$ m @ all interaction regions
Luminosity	2×10^{26} cm^{-2} s^{-1}
Interaction diamond length(rms)	20 cm

3. RHIC UPGRADE PLANS

The design luminosity in RHIC can be calculated from the parameters given in Table 3 according to the following equation:

$$L = \frac{3 f_{rev} \gamma}{2} \frac{N_b N^2}{\epsilon \beta^*} = 9 \ldots 1 \times 10^{26}\ cm^{-2}\ s^{-1} \text{ over 10 hours} \tag{1}$$

where f_{rev} is the RHIC revolution frequency of about 80 kHz. The drop in luminosity over the 10 hour store is due to intra-beam scattering which causes emittance growth. A first upgrade of the RHIC luminosity by a factor of four can be achieved by doubling the number of bunches to about 120 and by increasing focussing at the interaction regions to reduce the beta function by 50%.

Further upgrade of the luminosity requires that the emittance growth from intra-beam scattering is reduced or eliminated. Presently studies have begun to investigate the possibility to use high energy electron beams to cool the gold beams in RHIC. The electron beam intensity required for such a cooler are quite high and will require a high degree of recovery of the beam power. This could be accomplished using super-conducting accelerating/decelerating structures.

ACKNOWLEDGMENT

The highly successful commissioning and first operation of RHIC was made possible by the excellent and dedicated RHIC design and construction team and commissioning team.

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